Pergamon

0042-6989(95)00075-5

Vision Res. Vol. 35, No. 22, pp. 3093–3102, 1995

0042-6989/95 $9.50 + 0.00

An Illusion of Relative Motion Dependent Upon Spatial Frequency and Orientation

TREVOR J. HINE,*† MICHAEL COOK,‡ GARRY T. ROGERS*§

Received 16 August 1993; in revised form 6 June 1994; in final form 1 March 1995

Observers scanned a stationary pattern comprising a tilted sine-wave grating completely surrounding another grating of similar spatial frequency but tilted in the opposite direction (Fig. 2). They reported an illusory "sliding" motion of the inset grating with respect to the surround grating and the effect was clearly strongest for angles between the gratings of less than 60° and for spatial frequencies between 6–11 cpd. In a second experiment, a similar pattern was moved (2.0 deg/sec) either up or down for a presentation time of 167 msec. Simultaneously, the inset grating was drifted at different speeds in each of its two directions. Using the method of constant stimuli, it was shown that the relative motion illusion could be cancelled by physically drifting the grating in the opposite direction to the illusory movement. The illusion arises because there is a failure to integrate two motion signals into the single motion vector which characterises rigid motion.

Illusion Motion Spatial frequency Orientation Eye movement

INTRODUCTION

The Japanese graphic artist H. Ouchi has produced stationary, black-and-white checkerboard patterns which generate a particularly striking illusion of relative motion (Ouchi, 1977; Spillman, Tulunay-Keesey & Olson, 1993; Fig. 1). On the basis of exploratory studies with variants of the Ouchi pattern, we found that the checkerboard pattern is not necessary for the occurrence of the illusion. Rather, the oblique components of lower spatial frequency are important. Accordingly, our figure consists of two sinusoidally-modulated contrast gratings of differing orientations where one surrounds the other (Fig. 2), and this allows us to carefully characterise the spatial parameters of the illusion. When our figure is viewed at an appropriate distance, most observers normally report a "sliding" motion of the inset relative to the surround.

The first experiment was designed simply to determine under what spatial frequency, contrast and orientation conditions this new illusion of relative motion occurs. Since the illusion is so striking, informal observations were used to test some of the hypotheses about parameters. Some of these observations were presented at the Australian Experimental Psychology Conference (Hine & Cook, 1993).

*Optical Sciences Centre, RSPhysSE, Australian National University, Canberra, ACT 0200, Australia.

†To whom all correspondence should be addressed at the present address: School of Applied Psychology, HBS, Griffith University, Queensland 4111, Australia.

‡Department of Psychology, The Faculties, Australian National University, Canberra, ACT 0200, Australia.

§Present address: Department of Psychology, Monash University, Clayton, Victoria 3168, Australia.

EXPERIMENT 1: FREE SCAN

Apparatus and stimuli

The stimuli were displayed on a Tektronix 690SR colour monitor controlled by a custom-built colour graphics interface (PDI—James Sokoll Pty Ltd, Milton, Qld, Australia). Resolution of the display was 512 × 512 pixels refreshed at 60 Hz non-interlaced with each gun driven by a 12 bit DAC. The monitor was free-viewed binocularly in a front-silvered mirror within a light-tight tunnel and was placed 210 cm from the observer's eyes. Graphics and data collection were controlled by a laboratory minicomputer. The observers were two of the authors who possessed normal or corrected-to-normal visual acuity and normal colour vision.

Our stimulus was similar to the pattern illustrated in Fig. 2. In detail, it was superimposed on a bright, constant white background (chromaticity: $x = 0.33$, $y = 0.34$, luminance: 149 $cd \cdot m^{-2}$), 5.85 deg a side. The stimulus was annular, with the outer ring ("surround") subtending 2.9 deg which was twice the diameter of the inner disk ("inset"). Both the inset and surround were striped with one-dimensional sine-wave modulations of achromatic contrast of the same spatial frequency. The mean luminance of this waveform was the same as the background. As illustrated in Fig. 2, the surround and inset gratings were tilted symmetrically about the vertical axis: $\theta/2$ degrees to the left and right, respectively.

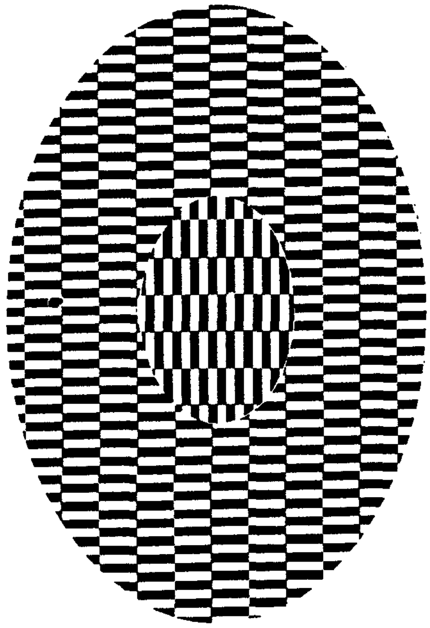

FIGURE 1. A variant of the original checkerboard pattern published in Ouchi (1977, p. 75). When viewed from *ca* 40 cm, the oval inset will spontaneously seem to "move" with respect to the surrounding checkerboard, appearing either as an aperture or an occluding figure.

Procedure

Stimuli were generated for nine spatial frequencies: 1.5, 2.3, 3.5, 5.1, 6.7, 8.7, 9.7, 10.9 and 14.5 cycles per degree (cpd), for each of the following five θs: 22.5, 45, 60, 90 and 135 degrees (°). A sixth angle condition (HV) was also tested: the inset grating was oriented vertically and the surround grating was oriented horizontally. The resolution of our graphics system did not permit us to adequately test spatial frequencies beyond 14.5 cpd.

Pilot work had indicated that the strength of illusion was dependent upon the "visibility" of the stimulus. We controlled for this by first determining each observer's threshold contrast for each combination of spatial frequency and angle. A particular stimulus was subsequently presented at a constant multiple of its threshold contrast. A method-of-adjustment procedure was used to measure a threshold where the grating structure of the stimulus could just be resolved. The stimulus was flashed for 1.3 sec every 1.5 sec upon the constant background. A minimum of five threshold levels were averaged for each observer for each angle and frequency combination.

The observer's task was identical in all subsequent parts of the experiment. An experimental run consisted of separate, 8.0 sec duration presentations of the stationary stimulus. The observer controlled the rate of these presentations. With his head fixed in a chin and forehead restraint, the observer was asked to continuously scan all parts of the stimulus. After each presentation, the observer was required to press one of two buttons on a response box to indicate whether he had perceived any apparent "sliding" of the inset of the figure with respect to the surround. If such apparent motion was perceived, then the observer was further required to press one of four buttons on the response box to indicate the "strength" of this apparent motion. He judged the strength of the illusion using two criteria: the number of times the apparent relative motion occurred during the presentation time, as well as the "size" of these apparent displacements.

In the first part of the experiment, an experimental run consisted of five stimulus presentations for each of the nine spatial frequencies for a fixed θ. Within a run, the trials were presented in a random order. Data from at least three runs were collected for each θ. Each stimulus was presented at a high contrast which was 38 times the observer's threshold, except for $\theta = 90°$ and 135° where the high thresholds at the finer spatial frequencies precluded us from presenting all spatial frequencies at 38 times threshold, given the contrast limits of our graphics system. At these angles, the gratings at all spatial frequencies possessed at least 21 times threshold contrast.

In the second part of the experiment we varied the contrast of a stimulus which had elicited a strong and reliable illusion in the first part of the experiment: $\theta = 45°$ at 9.7 cpd. A run consisted of seven stimulus presentations at each of seven contrast levels ranging from 4 to 48 times threshold. Trials were again presented in a random order with data from five runs collected for each observer.

RESULTS

The percentage of trials on which the observer had perceived the "sliding" of the inset was averaged for each angle and spatial frequency combination. Responses from the four buttons corresponding to the observer's rating of the "strength" of the illusion were scored as integers where four was the highest rating corresponding to the strongest illusion and zero was assigned to trials in which no illusion was seen. These ratings were then averaged for each spatial frequency and angle combination.

Figure 3 presents data from the first part of the experiment. The curves were very similar for the two measures of the illusion and both observers performed similarly. It is clear that there was an interaction between angle (θ) and spatial frequency. This could be accounted for by the fact that the illusion seemed to occur reliably only for quite acute θs just when the spatial frequency was between 6 and 12 cpd. The highest spatial frequency of 14.5 cpd produced very little illusory motion and the effect also lessened at lower spatial frequencies to be virtually non-existent at 1.5 cpd. Figure 4 presents the results averaged within each observer for a stimulus which generated a powerful illusion at high contrast and subsequently tested over a range of contrasts. This illusion was extremely weak at the lowest contrast, even though the grating pattern in the stimulus was quite visible (at four times threshold, Michelson contrast of the grating was about 4% for both observers). The

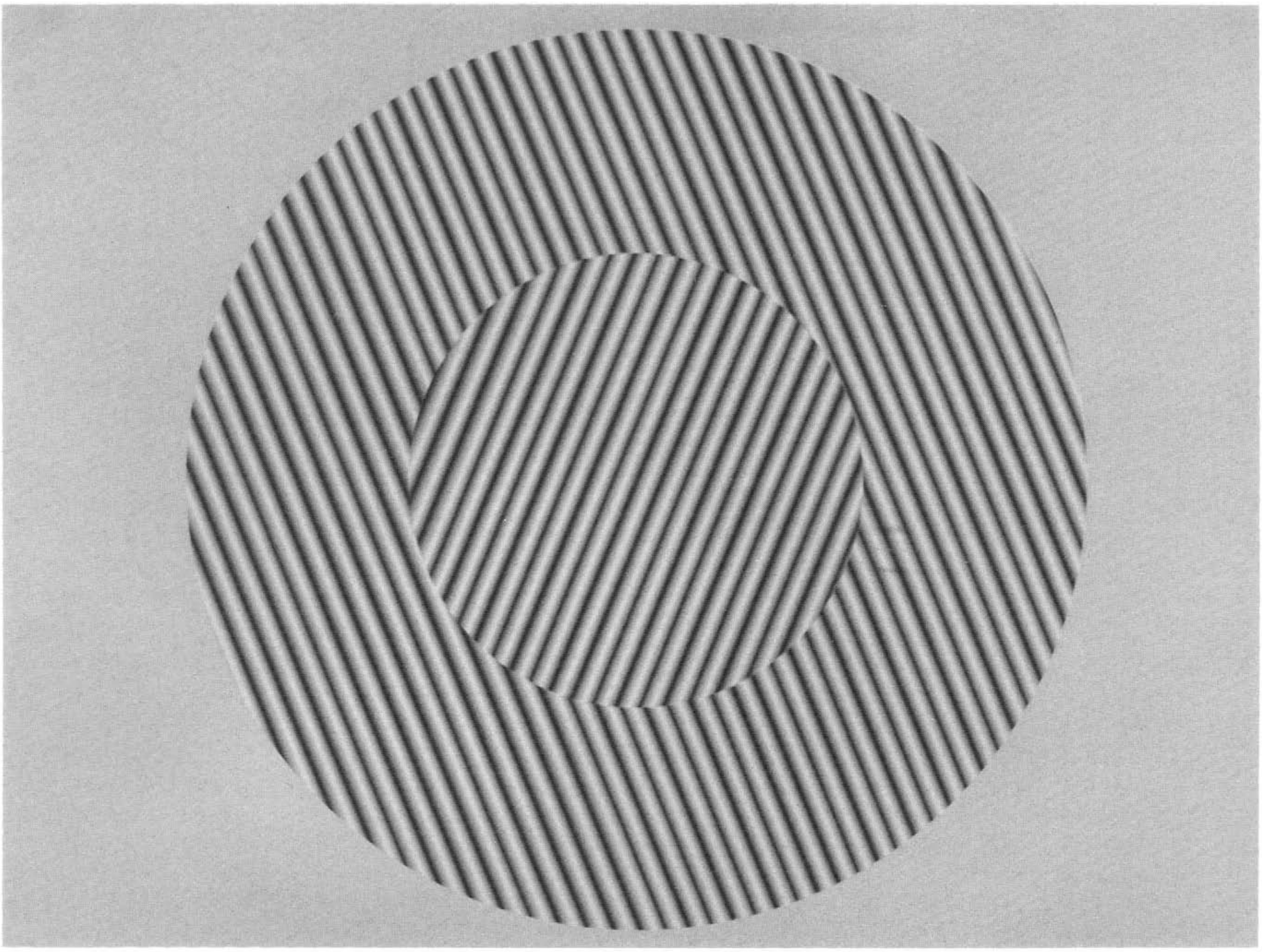

FIGURE 2. Figure similar to stimulus used in Expt 1. In the experiment, the surround and inset gratings were tilted symmetrically about the vertical meridian each by an angle of $\theta/2$ from this meridian. When viewed at *ca* 1.5 m and gently "jiggled" up and down at *ca* 3 Hz, the inner disk seems to slide to-and-fro above the outer ring, or as if seen through an aperture. The effect is not as pronounced if the figure is held sideways before being jiggled up and down. Holding the figure at other angles produces intermediate effects. Further demonstrations using this figure are described in text.

illusion increased monotonically in strength as the contrast was raised.

Informal observations

We observed that any illusion of relative motion during the experimental stimulus presentation was predominantly seen in the inset rather than the surround, and always in a direction orthogonal to the grating orientation. We made further informal observations of variations on the experimental stimulus rendered on paper in very high contrast. Monocular viewing does not diminish the illusion. It was observed that for the optimum spatial frequency, reducing the number of periods in the grating did not greatly reduce the strength of the illusion, *provided* that there were at least around 3–4 cycles in the stimulus. When θ is very acute, the illusion is difficult to observe and it fails when $\theta = 0$ where the inner grating is merely phase-shifted with respect to the surround. The illusion continues to work even if the inset and surround gratings are separated by a considerable gap, or if the surround is replaced by two separate gratings which flank the inset.

The illusory relative motion can be driven determinately by eye movements tracking a small target moving in front of the stationary figure: this can be tested using Fig. 2. The direction of tracking is critical. If it forms a sharp acute angle ($<45°$) with the component gratings (for example, a vertical direction of tracking movement combined with $\theta = 45°$ in Fig. 2), then a strong illusion of "sliding" is produced which is independent of the absolute orientation of the gratings. On the other hand, tracking movements in the orthogonal direction only weakly elicits the illusion. The same effects can also be produced by moving the whole figure in the appropriate direction behind a stationary fixation point. Most importantly, in all these cases, the direction of apparent relative motion of the inset was orthogonal to the grating orientation, and in the same general direction as the overall motion.

DISCUSSION OF EXPERIMENT 1

The present illusion can be differentiated from other familiar illusions of motion in stationary figures. Wade (1978) has drawn attention to apparent "pulsating" or

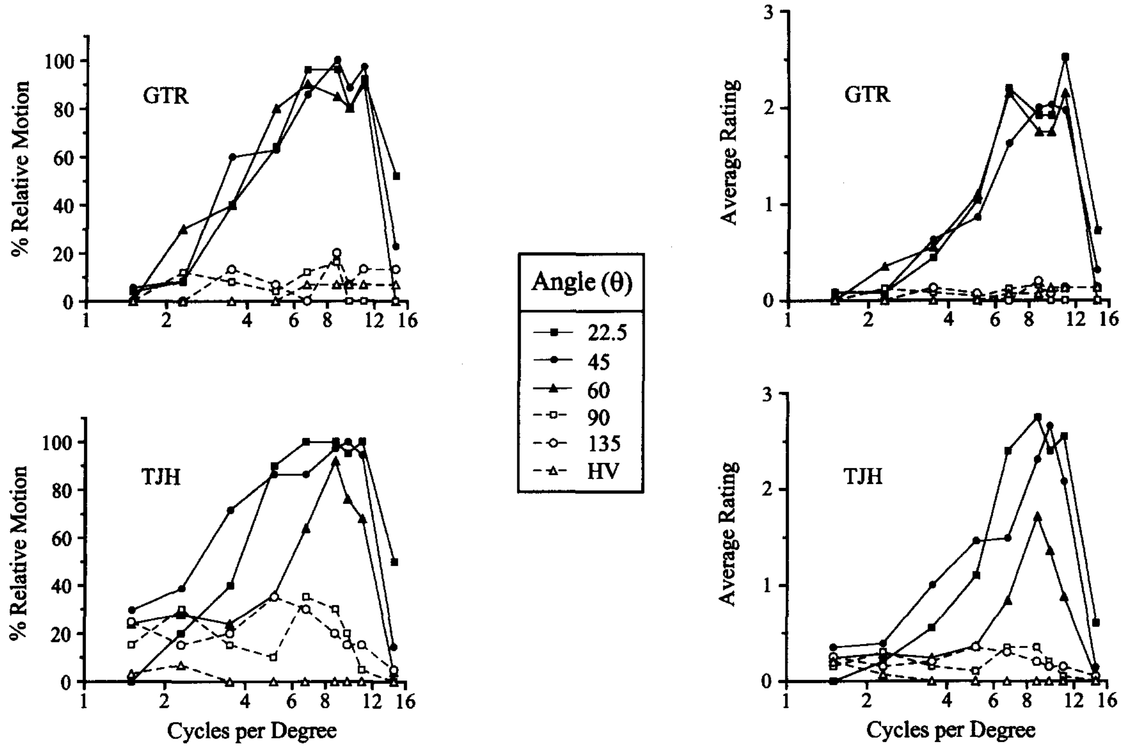

FIGURE 3. Strength of the relative motion illusion as a function of the angle θ and spatial frequency of the stimulus, plotted for each observer. In HV, the inset was vertical and surround horizontal. Left hand graphs are the percentage of trials on which observers reported the illusion ("% relative motion"), right hand graphs record the average ratings of the illusion's strength ("average rating"). For both these measures, the acute angles ($\theta < 90°$) produced a greater illusory effect than obtuse angles (*post hoc* means comparisons: % relative motion: $F(1,5) = 59.0$, $P < 0.05$; average rating: $F = 104.1$, $P < 0.05$). Also, the illusion was much stronger for spatial frequencies between 6 and 12 cpd when compared to both the higher and lower spatial frequencies (*post hoc* means comparisons: % relative motion: $F(1,8) = 115.7$, $P < 0.05$; average rating: $F = 265.9$, $P < 0.025$).

"jazzing" motion seen in the physically stationary, fine-grained repetitive patterns of Op Art which occurs in the absence of eye movements (Kupin, Haddad & Steinman, 1973). Campbell and Robson (1958) proposed that these "jazzing" effects are due to small astigmatic fluctuations in the lens of the eye. This cannot be the basis of the present effect, because it works during pinhole viewing which strongly suppresses any astigmatic error, using a stimulus composed of medium, rather than very high, spatial frequencies. The fact that an aphakic observer has reported seeing the inset of Fig. 1 "jiggling around" constitutes further evidence that it is not caused by fluctuations in accommodation (Campbell, Robson & Westheimer, 1959). Our effect can also be distinguished from movement effects seen in moiré patterns (Spillmann, 1993), as well as the "streaming" effects evident both in ray figures (MacKay, 1957) and a combination of the latter figures with concentric ring patterns (Zeki, Watson & Frackowiak, 1993; Gregory, 1993; Zeki, 1994). In the present stimulus, the *entire* centre of the figure appears to move in a coherent and smooth fashion when fixated and scanned, whereas the other effects are both random and piecemeal, occurring somewhat eccentric to the fixation point. Finally, it is not an example of the classic induced motion illusion (Duncker, 1929/1938; veridical motion of one pattern adjacent to another stationary pattern causes the latter to appear to move), since relative motion is seen when there is no physical movement of one part of the stimulus with respect to any other part.

Any illusory movement of the inset or surround is seen as orthogonal to the orientation of grating's "wavefront" (see Fig. 2). Given that local motion detectors necessarily resolve motion as being orthogonal to the grating wavefront (the "aperture problem"; Adelson & Movshon, 1982), then the illusion seems to arise from a breakdown in the spatial integration of local motion measures into a global, coherent movement. This breakdown occurs, though, only for the acute angles. In fact, we found a large difference in the strength of the illusion for $\theta = 45°$ vs $\theta = 135°$, even though the stimulus corresponding to the latter angle is simply the former rotated through 90°. This difference cannot be accounted for by simple anisotropies in motion sensitivity due to absolute retinal orientation of the motion direction, since van de Grind, Koenderink, van Doorn, Milders and Voerman (1993) found no discernible anisotropy in the fovea for motion directions equally spaced either side of the vertical meridian.

There is a more plausible explanation for our clear difference in results between $\theta = 45°$ and $\theta = 135°$. Even though eye scanpath was not directly measured, both observers believed that they had followed instructions and had made eye movements in all directions over the stimulus during the eight second inspection period. Note that horizontal eye movements would cause slippage of

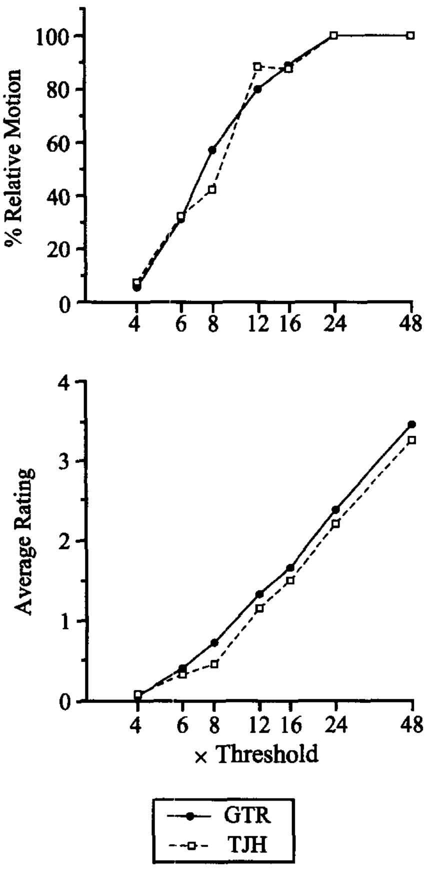

FIGURE 4. Strength of the relative motion illusion as a function of contrast for the stimulus $\theta = 45°$ at 9.7 cpd. The illusion is extremely weak at the lowest contrast and increases in strength as contrast increases.

the figure's image upon the retina at a sharp angle with respect to the gratings for $\theta = 135$, yet the illusory percept was weak at this angle. Then again, Ilg and Hoffmann (1993) have recently reported that the visual system is more sensitive to horizontal movement of the visual field which occurs *during* a saccade, than it is to vertical movement. This effect is independent of the saccade direction itself. Relating these findings to our results, the illusory relative motion for $\theta = 45$ has its main component in the horizontal direction and hence is more easily detectable than for $\theta = 135$, where the motion direction is more vertical.

The illusion gains strength monotonically as contrast is increased and works most reliably for Michelson contrasts of 25% and above. This dependence on contrast suggests that it is induced by movement of the retinal image which occurs during saccades as the observer inspects the figure. During a saccade, contrast sensitivity is reduced by an order of magnitude, but just for low spatial frequencies (Volkmann, Riggs, White & Moore, 1978; Burr, Holt & Ross, 1982; Burr, Morrone & Ross, 1994). Our stimulus comprises not only the high spatial frequencies of the surround and inset gratings, but also the much lower spatial frequencies of the bounding contours of each of the inset and surround. Thus, the latter contours evidently form an important component of our relative motion illusion. In this respect, our illusion can be considered the converse of the "motion capture" effect (MacKay, 1961; Ramachandran & Inada, 1985; Ramachandran & Cavanagh, 1987). In motion capture, a high spatial frequency pattern of random dots is perceived to move coherently (rigidly) with a low spatial frequency grating moving at a different velocity. In our case, incoherent (relative) motion is seen when all parts of the stimulus move as one.

The uncontrolled nature of the scanning eye movements in Expt 1 poses a problem in formulating an explanation of the illusion. A report of recent research utilizing retinally stabilised images (Spillmann *et al.*, 1993) indicated that illusory relative motion is perceived when the image of an Ouchi checkerboard pattern is physically moved on the retina, independent of any image movement generated by fixational eye movements. In Expt 2 described below, we have tried to circumvent the effects of eye movements by moving our stimulus behind a fixation point for a very short period of time. Simultaneously, the inset grating was physically drifted within its "aperture" at various velocities in an attempt to "cancel" or "null" the illusion of relative motion. We chose this method because the illusion seems to involve the sensation of smooth motion without positional changes which is indicative of the involvement of "short-range" motion processes (Sekuler, Anstis, Braddick, Brandt, Movshon & Orban, 1990). Also, since the presence of the surround grating seems a necessary condition for the illusion's occurrence, we obtained control data with no surround.

EXPERIMENT 2: MOTION CANCELLATION

Apparatus and stimuli

The same apparatus, viewing conditions and observers were used as in Expt 1. Unlike the first experiment, the whole stimulus (Fig. 5) moved either up or down the TV screen behind a prominent fixation point while simultaneously the inset grating drifted within its "aperture" (see below). Also, the inset was separated from the surround by a ring, 0.17 deg in width and of the same white colour as the background. This gap prevented the drifting inset grating from directly abutting the surround grating. It was designed to attentuate "shearing" relative motion cues between the two gratings. The stimuli were always presented at 25% contrast which was at least 20 times threshold for all spatial frequencies used.

A trial constituted the displaying of a motion sequence of ten frames. Each frame lasted 1/60th of a second for a total stimulus presentation time of 167 msec. In the first frame, the stimulus appeared in the centre of the screen. During the next nine frames, the whole stimulus moved vertically either up or down the screen for 0.31 deg at a constant 2.07 deg/sec before disappearing. In each of those same nine frames, the grating within the inset could be "scrolled", normally just by the equivalent of one pixel per frame. The surround grating was not scrolled. We were able to achieve slow, smooth drifting of the inset grating at various velocities by varying the

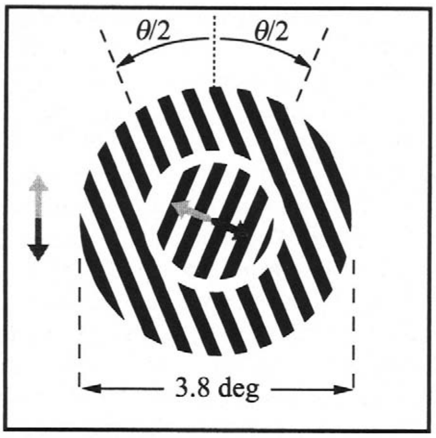

FIGURE 5. Schematic stimulus used in Expt 2, with sine-wave modulated gratings of the same spatial frequency in the inset and surround represented here by bars. A fixation bead (0.1 deg dia) was affixed to the screen over the centre of the stimulus, and whole pattern moved either vertically up or down the screen (represented by arrows to the left of stimulus). Simultaneously, the inset grating drifted either predominantly "with" (arrows of the same shading) or "against" (arrows of different shading) the direction of overall motion. In the No Surround condition, the surround grating was absent (i.e. no contrast modulation with respect to the background).

number of frames per motion sequence in which the grating was scrolled. Velocities could be doubled by having the inset grating scroll the equivalent of two pixels at a time rather than just one. When the inset grating was drifted it gave the impression of disappearing underneath the aperture. The direction of drift was always orthogonal to the grating orientation and either in the same general direction as overall movement ("with" drifting indicated by arrows of the same shading in Fig. 5) or in the exact opposite direction ("against" drifting indicated by arrows of different shading).

Both the direction of overall motion and the starting phase of the inset grating were randomised from trial to trial. We were able to minimise positional cues using the latter method so that the observer was unable to ascertain by what amount the inset had drifted simply by noting (e.g. through "inspection" of the afterimage) the final position of the inset grating relative to surround grating or bounding contours, and then comparing this to similar positional information gleaned from previous trials. Also, any effect of eye movements was negligible. In fact, because of saccadic suppression, observers were virtually unable to recognise the stimulus if they moved their eyes from the fixation bead during a trial. Moreover, since the direction of overall movement was randomised, the observer could not reliably anticipate the stimulus. For these reasons, we can be confident in discounting the possible effects of saccades, including express saccades (Kingstone & Klein, 1993). Finally, smooth pursuit is completely ineffective for the frequency and amplitude of our stimulus movement (Martins, Kowler & Palmer, 1985).

Procedure

The method of constant stimuli was used in conjunction with a forced choice paradigm. Observers were well practised in the task before data were collected. Each session consisted of 450 self-paced trials which lasted about 20 min, including a short intermission. During a session, the angle θ in Fig. 5 was fixed at either one of 22.5°, 45°, 60° or 135°. The angle 90° was not used due to minor "aliasing" anomalies in the image whereby at the finest spatial frequency, drifting the "inset" produced a small but unacceptable amount of "twinkling" in the high-contrast image which constituted a weak artefactual cue to relative motion. Five spatial frequencies of sine-wave modulation were tested within a session: 14.5, 9.7, 4.8, 3.2 and 1.6 cpd. Fifteen levels of inset grating drift velocity were presented and 12 of these levels corresponded to scrolling the inset grating each of one to six pixels per motion sequence both with and against the overall stimulus movement. Another level consisted of no drifting of the inset. The final two levels were the perceptual "anchors": the inset was drifted twelve pixels both with and against overall motion and the observers always correctly reported seeing drifting of inset within its aperture. The stimulus (Fig. 5) appeared either with the surrounding grating absent ("No Surround", the control condition) or present ("Surround"). Three trials of each and every combination of Surround/No Surround, scrolling level and spatial frequency were presented in a session, with the order of trials completely randomised. Data from four sessions were collected over a number of days for each of the four angles, a total of 7200 trials for each observer.

On each trial, observers pressed one of two buttons depending on whether they perceived any drifting of the inset grating either within its aperture or relative to the surround grating, during the time the whole figure moved either up or down. A third response ("not sure") was allowed to facilitate the task for the observer. However, the observer was instructed to use this button very sparingly, and in fact less than 3% of responses were "not sure". Finally, a fourth button allowed for a particular trial to be replayed later during the same session, just in the rare case there was unintended eye movement during a trial (see above). Only two replays of a particular trial were allowed, after which a "not sure" response was automatically forced by the computer.

RESULTS

The observer's button responses were scored in the following way: perceived drifting of the inset relative to aperture or surround = 0, not sure = 1, no relative movement (that is, "*en bloc*" or rigid movement) = 2. Responses from the "anchor" trials constituting unambiguous relative motion (12 pixel scrolling) were discarded and data from the four sessions were combined. The number of pixels the inset was scrolled in a motion sequence was converted to local drift velocities of the inset grating. Examples of the resultant raw data are depicted in Fig. 6. These data are similar to grouped frequency data (Hays, 1977), where the number of times *en bloc* (rigid) motion was seen to occur is accumulated

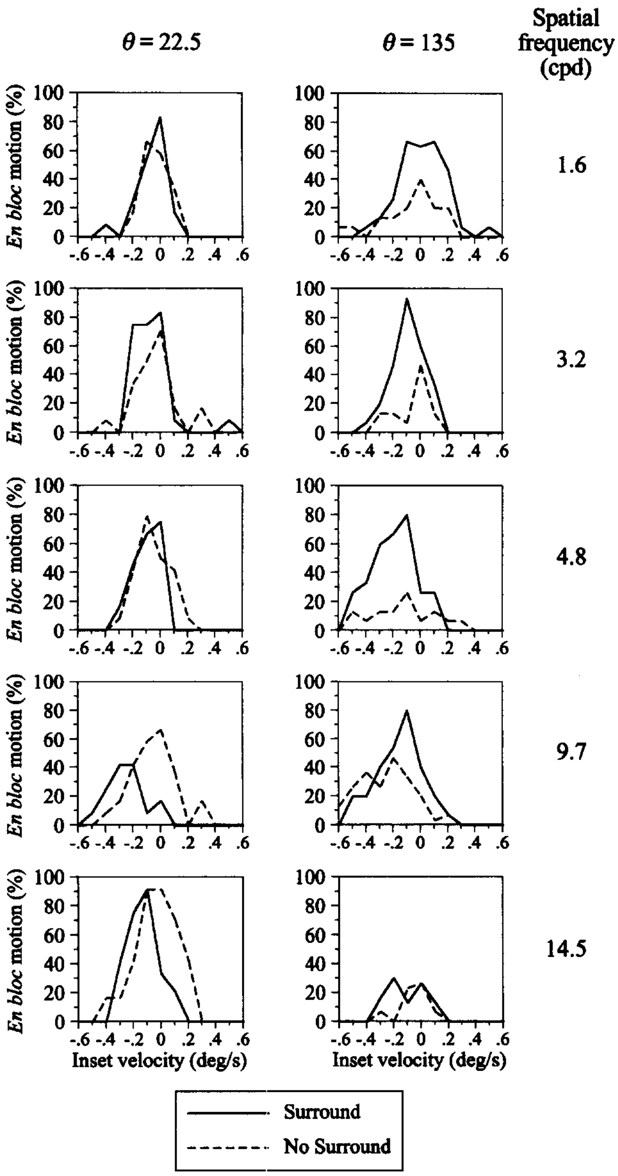

FIGURE 6. Examples of raw data from observer GTR for two angles between inset and surround ($\theta = 22.5°$ on the left and 135° on the right) at each of the five spatial frequencies. The control condition with the surround absent is indicated by the broken lines. The y-axis is equivalent to the percentage of trials the observer perceived the stimulus to move *en bloc* (the maximum score of 24 is equal to 100%, scoring details in text). The x-axis is equivalent to local drift velocities (deg/sec) of the inset grating orthogonal to its wavefront. Positive numbers are "with" drifting and negative numbers are "against" drifting (see Fig. 5). The centroids of the histograms correspond to the average velocity of the inset gratings at which the whole figure was perceived to move rigidly. For the acute angle, there was a difference in the location of this centroid between the Surround vs No Surround conditions, but just for 9.7 cpd.

for each of the thirteen inset velocities. The overall area under the resulting "histograms" in Fig. 6 is related to the willingness of the observer to press the button corresponding to *en bloc* motion. More importantly, if the observer were seeing the stimulus veridically, then these histograms should be centred upon zero velocity. In fact, there is small but clear bias towards "against" velocities. Moreover, there does not seem to be much difference in the amount of this bias between the "Surround" and "No Surround" conditions, except for $\theta = 22.5$ at 9.7 cpd.

To parametrise these biases in the raw data and thus obtain an estimate of the drifting rate of the inset grating which would "cancel" the relative motion illusion, we computed a measure of central tendency (M) and dispersion (SEM) in the raw data such that:

$$\mathrm{M} = \sum_{i=1}^{13} x_i s_i / N$$

$$\mathrm{SEM} = \left[\sum_{i=1}^{13} (x_i - \mathrm{M})^2 s_i \right]^{1/2} / N, \qquad (1)$$

where x_i = scrolling level, s_i = score for that level and $N = \Sigma s_i$. Thus, M was the centroid of the response histogram, weighted by the frequency of reported *en bloc* motion, and SEM was the second moment of the histogram. These averaged data for both observers and all angles are presented in Fig. 7. The raw and averaged data together indicate that the drift velocity of the inset grating which cancels any illusion of relative motion of this grating becomes much more negative when the surround is present than when it is not there, but just for the acute angles (especially 22.5°) and middle spatial frequencies (4.8 but especially 9.7 cpd). These values of angles and spatial frequencies match those from Expt 1 where the relative motion illusion was found to be at its strongest. Also, the fact that inset grating has to drift away from the general direction of overall motion to annul the illusion reinforces the observation in Expt 1 that the direction of illusory relative motion of the inset seemed to be always in the same general direction as the overall motion of the stimulus.

GENERAL DISCUSSION

The results of Expt 2 demonstrate clearly that the relative motion illusion investigated here is not dependent upon eye movements, confirming Spillman *et al.* (1993). Rather, eye movement is just one means of producing motion of the image of the stimulus on the retina, and, in turn, any image motion causes the illusion of relative motion. Second, the results of Expt 2, especially with the most acute angle, show that a second, or surround grating, is necessary for the illusion to occur. Finally, the illusion must be one of relative motion predominantly in the same direction as overall image motion, because a perception of rigid motion is produced by physically drifting the inset grating in the opposite direction to the overall motion.

Orientation effects

It is important to bear in mind that there is a difference of $(180 - \theta)°$ between the inset and surround local motion vectors in Fig. 6, such that acute angles between the gratings correspond to obtuse angles between the local motion vectors, and vice-versa. Thus, the illusion dissipates when the two local motion vectors from the inset and surround gratings are close to each other in direction. Our illusion is like the effect

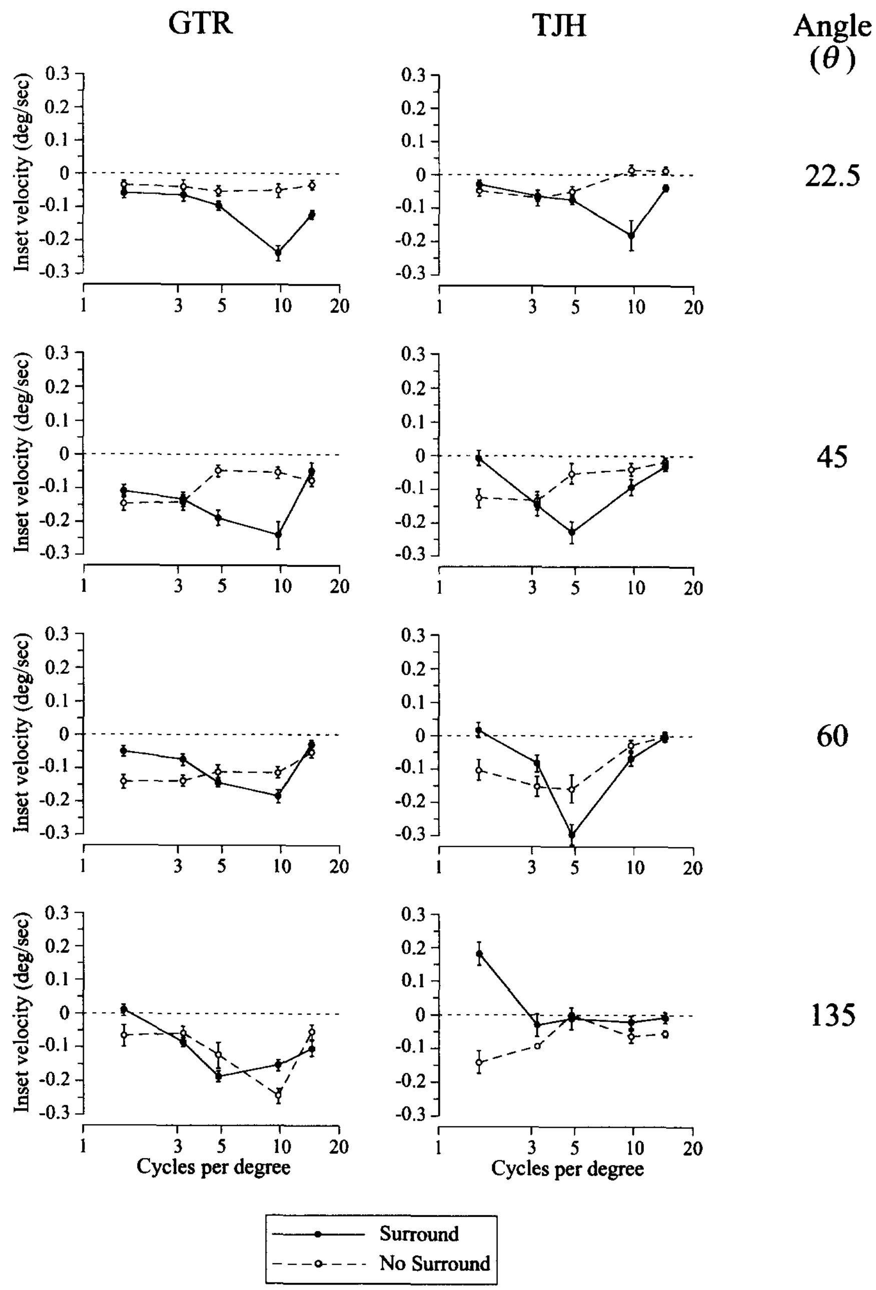

FIGURE 7. Averaged data for the two observers using equation (1), where error bars are ± 1 SEM. The y-axes are equivalent to the local drift velocities of the inset grating. As before, negative values correspond to "against" drifting velocities which are generally in a direction away from the overall stimulus movement. The x-axes are the spatial frequencies of the gratings. The data correspond to the average velocity of the inset at which there was a perception of rigid motion. The differences between the Surround/No Surround conditions tended to be greatest for the middle spatial frequencies and the more acute angles.

reported by Nakayama and Silverman (1988a, b), where nonrigid, or undulating motion is seen in a physically rigid "wavy" line of shallow amplitude as it is translated in the plane. Nakayama's explanation is that there is a low probability of integration of local motion vectors into global motion just if the local motion constraint lines are very close in direction, the very conditions under which our illusion occurs.

Our orientation effects in Expt 2 are not due to anisotropies in motion sensitivities, even though Raymond (1994) has recently reported that when the eye is stationary, observers were more sensitive to horizontal vs vertical motion direction. By observing the results of physically "jiggling" Fig. 2 in various directions, it becomes clear that absolute direction of both the overall and the two local grating motion vectors are not important. Rather, it is the presence of a large, obtuse angle between these local vectors that is crucial. The larger this angle, the greater the impression of directionally opposed motion between the local vectors and presumably the more difficult it is for the visual system to resolve such opposing motion as being produced by a single overall motion vector. Certainly, it has been found psychophysically that at least 120° is required between directions of motion to be certain of stimulating entirely independent motion mechanisms (Raymond, 1993; Ball, Sekuler & MacHamer, 1983; Mather & Moulden, 1980). Our proposal here is that our relative motion illusion occurs when different motion channels are being stimulated by each of the inset and surround.

However, results from Expt 1 clearly show that the illusion is at its weakest to the point of non-existence when the inset and surround gratings are orthogonal. Recent psychophysical and neurophysiological work has suggested that motion channels most sensitive to motion in a given direction will maximally suppress motion in the orthogonal direction (Snowden, 1989). Thus, the visual system would be least sensitive to relative motion in orthogonal directions, in line with our results.

Narrow spatial frequency range

The most perplexing finding in Expt 1 and 2 is the narrow spatial frequency bandwidth in which the illusion occurs: approximately 6–12 cpd, peaking at around 9 cpd. Given the image velocities and luminance levels encountered in both experiments, this bandwidth does not correspond to the maximum spatiotemporal sensitivity of the human visual system which occurs at 4 cpd or below (Kelly, 1979, Koenderink & van Doorn, 1979). On the other hand, recent neurophysiological work of von der Heydt, Peterhans and Dursteler (1992) characterises neurons (which they call "grating" cells) in the macaque areas V1 and V2 whose response patterns provide strong circumstantial evidence that they might underlie our relative motion illusion. The response of gratings cells and the illusion's strength are not only closely matched in spatial frequency, but in most other ways as well. Grating cells are specialised for the detection of periodic patterns within a small receptive field. They do not signal harmonic components but rather just the one, fundamental spatial frequency of a pattern. In this respect, von der Heydt *et al.* (1992) report that the cells respond vigorously to checkerboards of the appropriate spatial scale, similar to patterns used in the original "Ouchi" pattern (Fig. 1). They also require a couple of cycles of a periodic pattern before they start responding above spontaneous activity levels, and are directionally selective, but unaffected by motion velocity. Finally, von der Heydt *et al.* (1992, p. 1423) reports that "all these cells could be activated strongly by stationary ... gratings ... apparently the fixational eye movements are sufficient to maintain this activity". In all these instances there are parallels in data presented in this paper. These parallels have been developed further in Hine, Cook and Rogers (1995).

Figure/ground effects

There is a definite "figure/ground" effect in the illusion (see Figs 1 and 2). We found that almost all the time the appearance of movement was in the "figure", that is, the inset, as opposed to the "ground" or surround. Presumably the ground is stabilised with respect to an external, "absolute" frame of reference, e.g. the edges of the page or TV screen. We have generated "three-ring" patterns similar to Figs 1 and 2, where a central disk and outside ring are patterned the same way, and a middle ring consists of the pattern of opposite direction or tilt. In this case, the middle ring becomes the "figure" and hence it seems to move. However, in this case the illusion is "multistable": sometimes the central disk seems to move within the middle ring, or both the disk and middle ring move reciprocally within a stationary outer ring. Because the external frame of reference is lost in stabilised vision, in this case either part of Fig. 1 seems to move with equal facility (Spillmann *et al.*, 1993).

Conclusion

We have circumscribed some of the spatial conditions under which a recently discovered illusion of relative motion occurs. The illusion's existence implies that the visual system is ignoring two possible sources of veridical information as to the *absence* of relative motion: the lack of "shearing" between the inset and surround gratings at their boundary, as well as the lack of occlusion. In this respect, our effect is related to both motion capture and induced motion. de Valois and colleagues (de Valois & de Valois, 1991; Zhang *et al.*, 1993) have investigated both the latter effects with stimuli similar to ours whereupon fine, repetitive drifting patterns are bounded by contours forming apertures. A comprehensive explanation of the present effect will no doubt be subsumed in an explanation of all these effects. Such an explanation awaits further research.

REFERENCES

Adelson, T. & Movshon, J. A. (1982). Phenomenal occurrence of moving visual patterns. *Nature, 300,* 523–525.

Ball, K., Sekuler, R. & MacHamer, J. (1983). Detection and identification of moving targets. *Vision Research, 23,* 229–238.

Burr, D. C., Holt, J. & Ross, J. (1982). Selective depression of motion sensitivity during saccades. *Journal of Physiology, 333,* 1–15.

Burr, D. C., Morrone, M. C. & Ross, J. (1994). Selective suppression of the magnocellular visual pathway during saccadic eye movements. *Nature, 371,* 511–513.

Campbell, F. W. & Robson, J. G. (1958). Moving visual images produced by regular stationary patterns. *Nature, 181,* 362.

Campbell, F. W., Robson, J. G. & Westheimer, G. (1959). Fluctuations of accommodation under steady viewing conditions. *Journal of Physiology, 145,* 579–594.

Duncker, K. (1938). Induced motion. In Ellis, W. D. (Ed.), *A source book of gestalt psychology* (pp. 161–172). London: Routledge & Kegan Paul. (Original work published in 1929).

Gregory, R. L. (1993). A comment: MacKay Rays shimmer due to accommodation changes. *Proceedings of the Royal Society of London B, 253,* 123.

van de Grind, W. A., Koenderink, J. J., van Doorn, A. J., Milders, M. V. & Voerman, H. (1993). Inhomogeneity and anisotropies for motion detection in the monocular visual field of human observers. *Vision Research, 33,* 1089–1107.

Hays, W. L. (1977). *Statistics for the social sciences* (2nd edn). London: Holt, Rinehart & Winston.

von der Heydt, R., Peterhans, E. & Dursteler, M. R. (1992). Periodic-pattern-selective cells in monkey visual cortex. *Journal of Neuroscience, 12,* 1416–1434.

Hine, T. & Cook, M. (1993). A novel visual illusion of relative motion—the "Ouchi" illusion. *Australian Journal of Psychology, 45,* 114.

Hine, T., Cook, M. & Rogers, G. T. (1995). The Ouchi illusion: an anomaly in the perception of rigid motion for limited spatial frequencies and angles. *Perception & Psychophysics*. Submitted.

Ilg, U. J. & Hoffmann, K.-P. (1993). Motion perception during saccades. *Vision Research, 33,* 211–220.

Kelly, D. H. (1979). Motion and vision. II. Stabilized spatio-temporal threshold surface. *Journal of the Optical Society of America, 69,* 1340–1349.

Koenderink, J. J. & van Doorn (1979). Spatiotemporal contrast detection threshold surface is bimodal. *Optics Letters, 4,* 32–34.

Kingstone, A. & Klein, R. M. (1993). What are human express saccades? *Perception & Psychophysics, 54,* 260–273.

Kupin, J. J., Haddad, G. N. & Steinman, R. M. (1973). Saccades in Neal's "Square of Three". *Perception & Psychophysics, 14,* 298–300.

MacKay, D. M. (1957). Moving visual images produced by regular stationary patterns. *Nature, 180,* 849–850.

MacKay, D. M. (1961). Visual effects of non-redundant stimulation. *Nature, 192,* 739–740.

Martins, A. J., Kowler, E. & Palmer, C. (1985). Smooth pursuit of small-amplitude sinusoidal motion. *Journal of the Optical Society of America A, 2,* 234–242.

Mather, G. & Moulden B. (1980). A simultaneous shift in apparent direction: further evidence for a "distribution-shift" model for direction coding. *Quarterly Journal of Experimental Psychology, 32,* 325–333.

Nakayama, K. & Silverman, G. H. (1988a). The aperture problem I: perception of nonrigidity and motion direction in translating sinusoidal lines. *Vision Research, 28,* 739–746.

Nakayama, K. & Silverman, G. H. (1988b). The aperture problem II: spatial integration of velocity information along contours. *Vision Research, 28,* 747–753.

Ouchi, H. (1977). *Japanese and Geometrical Art.* New York: Dover.

Ramachandran, V. S. & Cavanagh, P. (1987). Motion capture anisotropy. *Vision Research, 27,* 97–106.

Ramachandran, V. S. & Inada, V. (1985). Spatial phase and frequency in motion capture of random dot patterns. *Spatial Vision, 1,* 57–67.

Raymond, J. E. (1993). Movement direction analysers: independence and bandwidth. *Vision Research, 33,* 767–775.

Raymond, J. E. (1994). Directional anisotropy of motion sensitivity across the visual field. *Vision Research, 34,* 1029–1037.

Sekuler, R., Anstis, S., Braddick, O. J., Brandt, T., Movshon, J. A. & Orban, G. (1990). The perception of motion. In Spillmann, L. & Werner, J. S. (Eds), *Visual perception: the neurophysiological foundations* (pp. 205–230). New York: Academic Press.

Snowden, R. J. (1989). Motions in orthogonal directions are mutually suppressive. *Journal of the Optical Society of America A, 6,* 1096–1101.

Spillmann, L. (1993). The perception of movement and depth in moiré patterns. *Perception, 22,* 287–308.

Spillmann, L., Tulunay-Keesey, U. & Olson, J. (1993). Apparent motion in normal and stabilized vision. *Investigative Ophthalmology & Visual Science, 34* (Suppl.), 1031.

de Valois, R. L. & de Valois, K. K. (1991). Vernier acuity with stationary moving gabors. *Vision Research, 31,* 1619–1626.

Volkmann, F., Riggs, L. A., White, K. D. & Moore, R. K. (1978). Contrast sensitivity during saccadic eye movements. *Vision Research, 18,* 1193–1199.

Wade, N. J. (1978). Op art and visual perception. *Perception, 7,* 21–46.

Zeki, S. (1994). The cortical *Enigma*: a reply to Professor Gregory. *Proceedings of the Royal Society of London B, 257,* 243–245.

Zeki, S., Watson, J. D. G. & Frackowiak, R. S. J. (1993). Going beyond the information given: the relation of illusory visual motion to brain activity. *Proceedings of the Royal Society of London B, 252,* 215–222.

Zhang, J., Yeh, S.-L. & de Valois, K. K. (1993). Motion contrast and motion integration. *Vision Research, 33,* 2721–2732

Acknowledgements—We would like to thank N. Wade and M. Srinivasan for pointing out possible explanations of the illusion, and to an anonymous reviewer for suggesting important experimental additions.